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# TEMPERATURE EFFECT ON THE MECHANICAL PROPERTIES OF ALUMINUM ALLOY 2124-T851

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AIR FORCE MATERIALS LABORATORY
**AIR FORCE WRIGHT AERONAUTICAL LABORATORIES**
**Air Force Systems Command**
**Wright-Patterson Air Force Base, Ohio 45433**

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This final report was submitted by the University of Dayton Research Institute, Dayton, Ohio, under contract F33615-74-C-5024, Job Order 73810678, with the Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio. Mr. David C. Watson, AFML/MXE, was the Laboratory Project Monitor.

This report has been reviewed by the Information Office (IO) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

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The test material, aluminum alloy/temper 2124-T851, was a 2.5 inch (63.5 mm) thick plate. Variation in the test material's strength, toughness and cyclic loading crack growth rate were examined as influenced by test temperature or furnace exposure temperature. The tensile strength, fracture toughness, and cyclic crack growth rate of the material was unaffected over

20. Abstract (Continued)

the temperature range of 72°F (22°C) to 200°F (93°C). A 400°F (204°C) test temperature caused a 26 percent reduction in strength from that of the room temperature tensile strength. A 1000-hour furnace exposure at 300°F (149°C), 350°F (177°C), and 400°F (204°C) reduced the room temperature yield strength by 8, 20, and 48 percent, respectively. A 300°F (149°C) environment is the maximum limit for an extended time service temperature; higher temperatures causing too severe of loss in load carrying capability. The fracture toughness varied very little over the temperature range of -100°F (-73°C) to 400°F (204°C). Even though the toughness tests are invalid by ASTM standards the apparent toughness, $K_Q$, is improved by the 400°F (204°C) 1000-hour furnace exposure. The cyclic crack growth test data for test temperatures of 72°F (22°C) to 200°F (93°C) fall in one wide scatter band. A test temperature of 400°F (204°C) accelerates the crack growth rate and the 0°F (-18°C) and -100°F (-73°C) test temperatures reduced the cyclic loading crack growth rate.

# FOREWORD

This final technical report was prepared by the University of Dayton Research Institute, Dayton, Ohio, under contract F33615-74-C-5024, Project No. 7381, "Materials Application," Task No. 738106, "Engineering and Design Data," Job Order 73810678, with the Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio. Mr. David Watson, AFML/MXE, was the Laboratory Project Monitor.

The author, Mr. Russell R. Cervay, was responsible for the direction of the program, and would like to extend recognition to Messers. Woleslagle, Eblin, and Marton of the University of Dayton for their supporting efforts in this program.

This report covers work conducted from March 1974 to September 1975. It was submitted by the author for publication in December 1975.

TABLE OF CONTENTS

## LIST OF ILLUSTRATIONS

## LIST OF TABLES

# SECTION I

# INTRODUCTION

This program was conducted to explore the variation in mechanical properties of aluminum alloy 2124-T851 thick plate caused by either test temperature or by a thermal exposure cycle. Aluminum alloy 2124 is a refinement of alloy 2024 with tighter controls on the composition. The test alloy, being a 2000-series aluminum alloy, should be capable of sustaining a service temperature of 350°F (177°C). The mechanical property test results are directly comparable to those of alloy 2024.

## SECTION II

## MATERIALS, SPECIMENS, AND PROCEDURES

The test material was a 2 1/2-inch-thick (63.5 mm) plate of aluminum alloy 2124-T851 purchased from the Aluminum Company of America (ALCOA). The chemical composition is listed in Table 1. The alloy is a refinement of alloy 2024. A composite of photomicrographs of the test piece is presented in Figure 1. The photomicrographs were prepared to confirm the grain orientation. The photos indicate that the longitudinal and transverse grain sizes are approximately equal and therefore the grain orientation could not be unequivocally defined. The material, being a 2000-series aluminum alloy, should be capable of sustaining its load-carrying capability at an elevated service temperature.

TABLE I

CHEMICAL COMPOSITION OF AL 2124-T851 BY WEIGHT PERCENT

| Si | Mn | Ti | Zn | Ni | Fe | Cr | Cu | Mg | Be | Others | Al |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.07 | 0.55 | 0.02 | 0.03 | 0.01 | 0.11 | 0.02 | 3.94 | 1.42 | 0.0003 | 0.05 ea.<br>0.15 tot. | Balance |

All specimens were cut from the test piece with the loading direction parallel to the longitudinal grain direction. Tensile specimens were machined according to Figure 2. Fracture toughness tests used the 1.0-inch size compact specimens in Figure 3 (configuration a). Constant amplitude cyclic crack growth tests used the 3/4-inch size compact specimen in Figure 3 (configuration b). Both configurations of the compact specimen had a (L-T) orientation.

Tensile and fracture toughness tests adhered to ASTM testing standards (References 1, 2). The cyclic crack growth tests followed accepted test practices of the material testing community. After failure of the cyclic crack growth specimens the crack front curvature was measured, following the technique outlined in Reference 2, and added to the surface trace measurements made during the testing to obtain a corrected crack length. A 30x traveling microscope was used to make the crack length measurements. The cyclic crack growth test data was reduced to its final form entirely by computer. The computer program used a modified incremental method; grouping nine data points at a time, three dissimilar functions (exponential, power, and linear) were fitted to the data. The best fitting function was then used for
(Text Continued on Page 6)

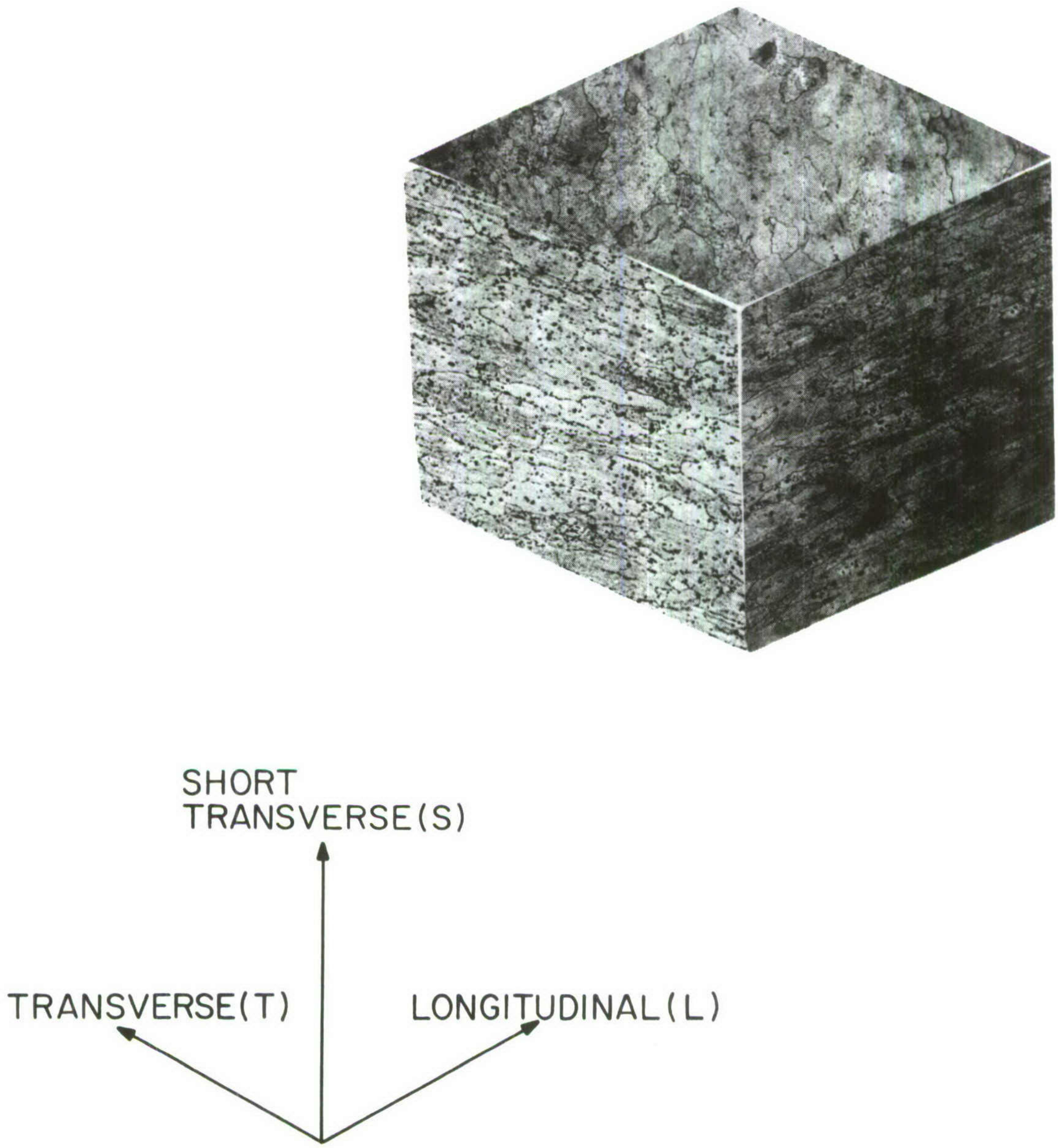



Figure 1. Microstructure and Aluminum Alloy 2124-T851 Rolled Plate (50x)

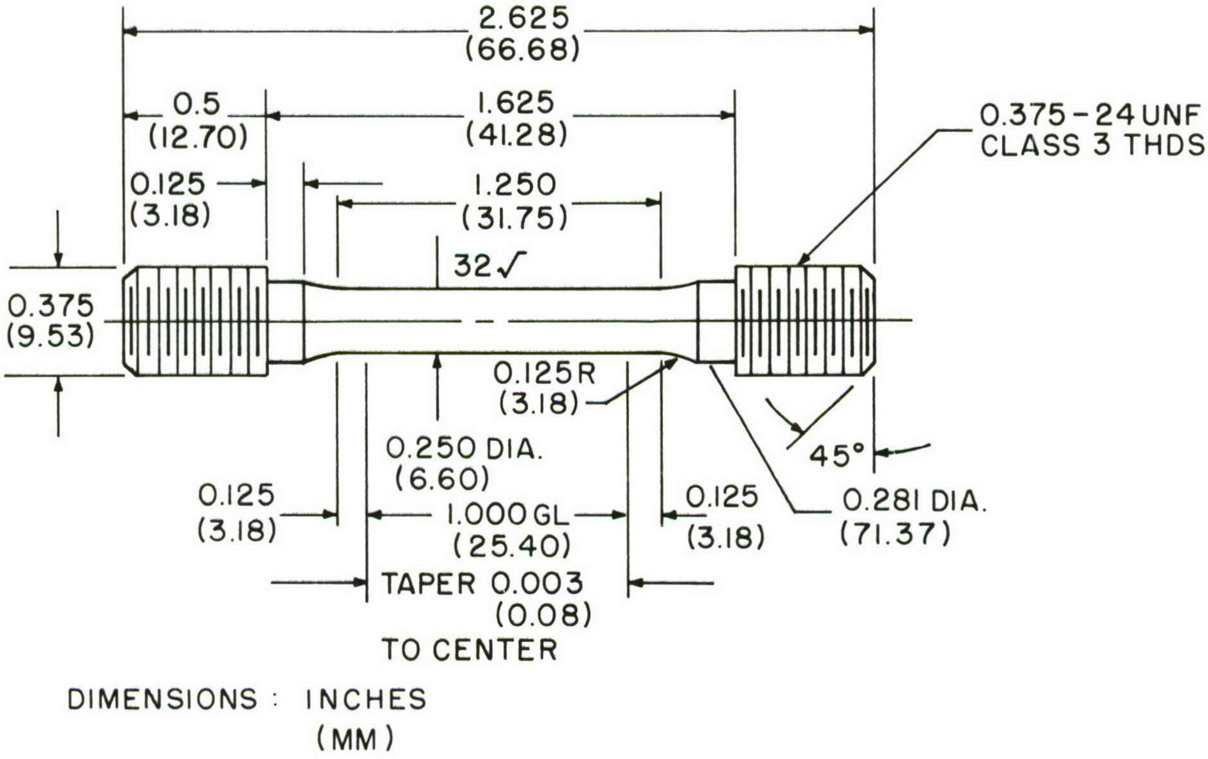
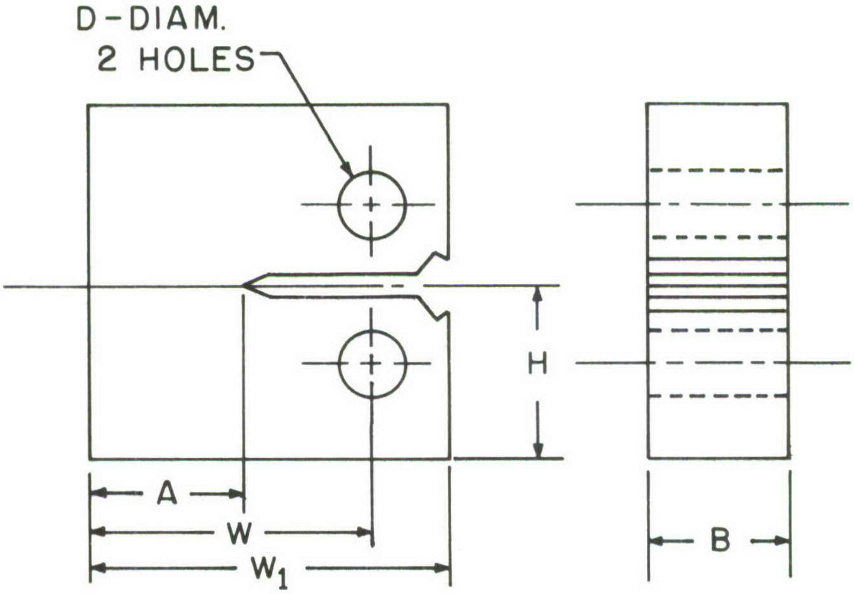



Figure 2. Tensile Specimen Configuration




DIMENSIONS

| SPECIMEN THICKNESS (INCHES) | A | B | W | $W_1$ | H | D |
|---|---|---|---|---|---|---|
| (a)* 1.0 (25.4) | 1.22 (31.0) | 1.0 (25.4) | 2.00 (50.8) | 2.50 (63.5) | 1.20 (30.5) | 0.50 (12.7) |
| (b) 3/4 (19.05) | 0.915 (23.2) | 0.750 (19.05) | 1.500 (38.10) | 1.875 (47.63) | 0.900 (22.86) | 0.375 (9.53) |

DIMENSIONS : INCHES
(mm)

Figure 3. Compact Specimen Configuration
(a) Fracture Toughness*
(b) Crack Growth

calculating the growth rate at the midpoint of the nine data points under consideration. The crack length at the midpoint of the subset was also used to calculate the stress intensity range. The first data point of the subset was then dropped and the next raw data point added to the subset. The curve fitting operation was then applied to the new nine data point subset.

The elevated temperature tests were conducted in a fully enclosed environmental chamber. The temperature was allowed to stabilize for one-half hour prior to the commencement of the test. All of the elevated temperature furnace-exposure specimens were in the heated furnaces for 1000 hours prior to undergoing a room temperature test.

## SECTION III

## RESULTS AND DISCUSSION

The reported observations are based on test results obtained from specimens that were machined from a single plate of aluminum alloy 2124-T851. Tensile test results are reported as a function of temperature in Table 2 and Figure 4. Tensile test results as a function of thermal cycling temperature are reported in Table 3 and Figure 5. A typical room temperature stress-strain trace is reproduced in Figure 6.

The ultimate and yield strength capabilities are equal to those previously reported for 2024-T851 in References 3 and 4. With a test temperature of 200°F (93°C) there is very slight loss of yield strength (6 percent); over the temperature range of -100°F (-73°C) to 200°F (93°C) there is minimal variation in the yield strength as shown in Figure 4. There is a 26 percent loss in yield strength with the 400°F (204°C) test temperature. Reference 4 indicates that alloy 2024 experiences the same loss of yield strength at a 400°F (204°C) test temperature.

Turning attention to the thermally cycled tensile specimen test data in Figure 5 and Table 3 there is little effect on the material's load carrying capability following a thermal cycle up to 250°F (121°C) when compared to data from specimens tested in the as-received condition. With the 300°F (149°C) - 1000 hour thermal cycle there is an 8 percent loss in yield strength. Considering strength alone, the maximum long-term service temperature should be approximately 300°F (149°C).

Fracture toughness test results are tabulated in Table 4. The test material's fracture toughness experiences little variation over the test temperature range of -100°F (-73°C) to 400°F (204°C). Reference 4 reports for the test alloy 2024-T851 that there is a constant toughness value over the temperature range of -65°F (-54°C) to 300°F (149°C). The room temperature fracture toughness test results fall within the wide data scatter band ($K_{IC}$ = 25 to 36 KSI$\sqrt{IN}$) reported in Reference 5 for 2124.

Thermally cycling the fracture toughness test specimens at 400°F (204°C) for 1000 hours before a room temperature test improved the apparent fracture toughness, $K_Q$, by 21 percent with a simultaneous 47 percent drop in yield strength which is responsible for the test results being invalid by ASTM test validity criteria.

The constant amplitude cyclic crack growth test results are presented in Figures 7 through 11. Figures 7 through 9 are the individual
(Text Continued on Page 14)

TABLE 2

TENSILE PROPERTIES OF ALUMINUM 2124-T851 (THICK PLATE)

| Specimen * | Test Temp. | Ultimate Strength (KSI) | Ultimate Strength (MPa) | Yield Strength (KSI) | Yield Strength (MPa) | Elongation in 1.0 in. (25.4 mm) (%) | Reduction Of Area (%) |
|---|---|---|---|---|---|---|---|
| 2L1 | -100 °F | 73.8 | 509 | 68.5 | 472 | 10.0 | 27.0 |
| 2L2 | - 73 °C | 74.2 | 512 | 67.5 | 465 | 7.0 | 20.0 |
| 2L3 | | 72.8 | 502 | 66.7 | 460 | 10.0 | 22.0 |
| | | 73.6 | 507 | 67.7 | 467 | 9 .0 | 23.0 |
| 2L4 | 0 °F | 70.9 | 489 | 65.4 | 451 | 8.0 | 21.0 |
| 2L5 | - 18 °C | 71.2 | 490 | 66.1 | 456 | 11.0 | 25.0 |
| 2L6 | | 72.5 | 500 | 66.4 | 458 | 10.0 | 32.0 |
| | | 71.5 | 493 | 66.0 | 455 | 10.0 | 26.0 |
| 2L7 | 72 °F | 70.1 | 483 | 64.5 | 445 | 8.5 | 17.0 |
| 2L8 | 22 °C | 69.3 | 478 | 64.4 | 444 | 11.0 | 23.0 |
| 2L9 | | 69.7 | 481 | 64.0 | 441 | 8.6 | 21.5 |
| | | 69.5 | 481 | 62.9 | 443 | 9.4 | 20.5 |
| 2L13 | 200 °F | 64.4 | 444 | 60.4 | 416 | 9.0 | 27.4 |
| 2L14 | 93 °C | 63.9 | 440 | 59.8 | 412 | 12.0 | 32.0 |
| 2L19 | | 67.4 | 464 | 62.1 | 428 | 9.6 | 26.4 |
| | | 65.3 | 450 | 60.8 | 419 | 10.0 | 28.6 |
| 2L16 | 400 °F | 53.5 | 369 | 49.5 | 341 | 17.0 | 62.0 |
| 2L17 | 204 °C | 51.4 | 354 | 47.0 | 324 | 17.0 | 54.0 |
| 2L20 | | 49.1 | 339 | 47.8 | 330 | 19.0 | 58.6 |
| | | 51.3 | 354 | 48.1 | 332 | 17.6 | 58.2 |

*All Tensile Specimens are Longitudinally Oriented

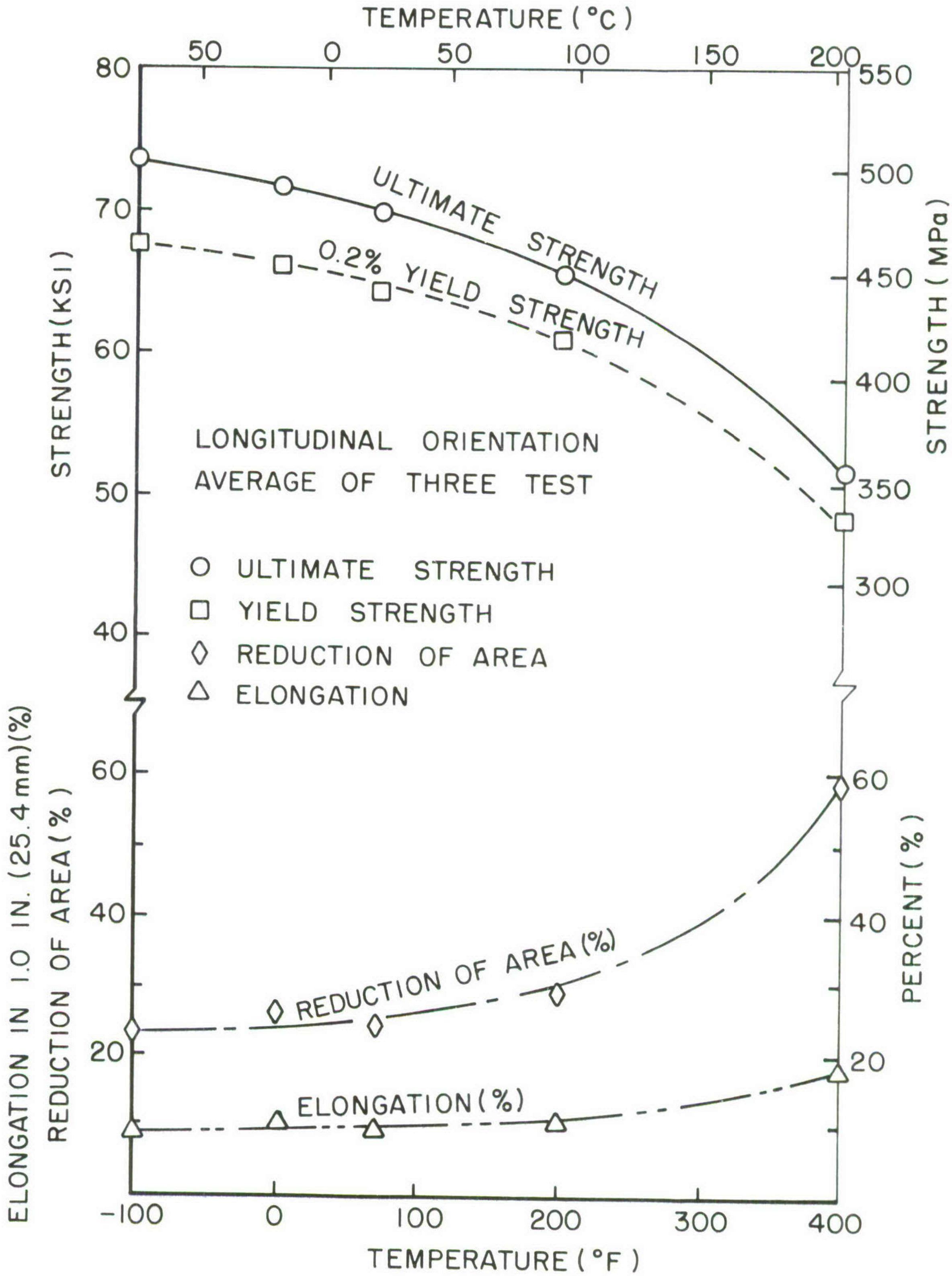



Figure 4. Tensile Properties of Aluminum Alloy 2124-T851 as a Function of Temperature

TABLE 3

ROOM TEMPERATURE TENSILE PROPERTIES OF ALUMINUM ALLOY 2124-T851 (THICK PLATE)

| Specimen No.* | Ultimate Strength (KSI) | Ultimate Strength (MPa) | Yield Strength (KSI) | Yield Strength (MPa) | Elongation (%) in 1 inch 25.4 mm G. L. | Reduction of Area (%) | Exposure |
|---|---|---|---|---|---|---|---|
| 2L7 | 70.1 | 483 | 64.5 | 444 | 8.5 | 17.0 | None |
| 2L8 | 69.3 | 477 | 64.4 | 444 | 11.0 | 23.0 | |
| 2L9 | 69.7 | 480 | 64.0 | 441 | 8.6 | 21.5 | |
| AVG. | 69.7 | 480 | 64.3 | 444 | 9.4 | 20.5 | |
| 2L21 | 69.8 | 481 | 64.4 | 444 | 8.4 | 23.0 | 250 °F (121°C) for 1000 hours |
| 2L22 | 70.3 | 488 | 65.6 | 452 | 11.1 | 30.0 | |
| 2L23 | 69.0 | 475 | 63.5 | 438 | 9.7 | 27.0 | |
| AVG. | 69.9 | 481 | 64.5 | 445 | 9.7 | 27.0 | |
| 2L24 | 68.7 | 473 | 60.1 | 414 | 9.1 | 25.6 | 300 °F(149°C) for 1000 hours |
| 2L25 | 67.9 | 468 | 59.3 | 409 | 8.3 | 19.6 | |
| 2L26 | 68.3 | 470 | 59.8 | 412 | 10.2 | 28.4 | |
| AVG. | 68.3 | 470 | 59.7 | 411 | 9.2 | 24.5 | |
| 2L27 | 62.6 | 431 | 50.9 | 350 | 7.5 | 18.7 | 350 °F(177°C) for 1000 hours |
| 2L28 | 62.2 | 428 | 50.9 | 350 | 8.6 | 20.4 | |
| 2L29 | 63.1 | 435 | 51.8 | 357 | 7.0 | 18.9 | |
| AVG. | 62.7 | 432 | 51.2 | 353 | 7.7 | 17.3 | |
| 2L10 | 50.6 | 348 | 34.8 | 240 | 11.0 | 23.0 | 400 °F(204°C) for 1000 hours |
| 2L11 | 50.1 | 345 | 33.1 | 228 | 11.0 | 21.0 | |
| 2L12 | 48.5 | 334 | 32.9 | 226 | 10.0 | 15.0 | |
| AVG. | 49.7 | 342 | 33.6 | 231 | 10.6 | 20.0 | |

*All Specimens Longitudinal Orientation

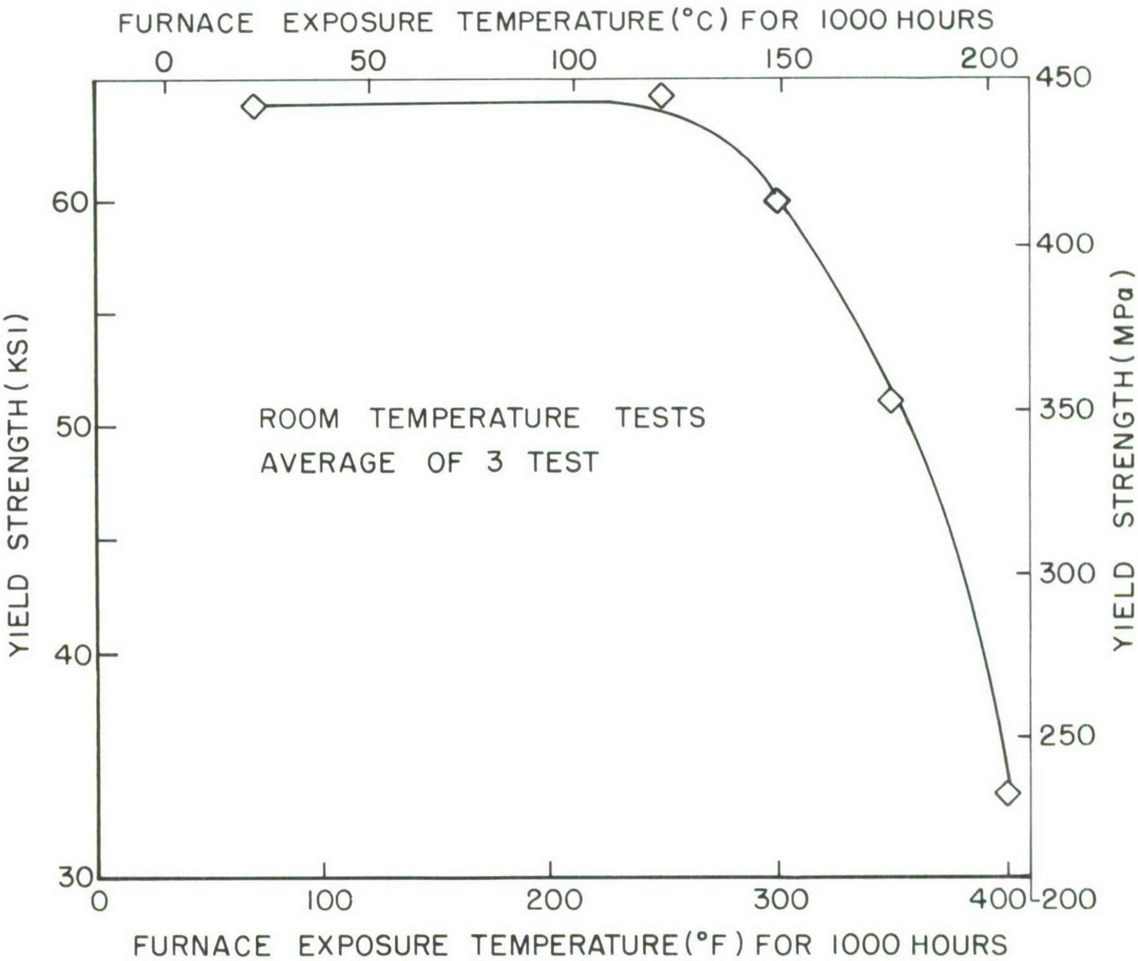



Figure 5. Variation in Room Temperature Yield Strength of Aluminum Alloy 2124-T851 Following a 1000 Hour Furnace Thermal Cycle

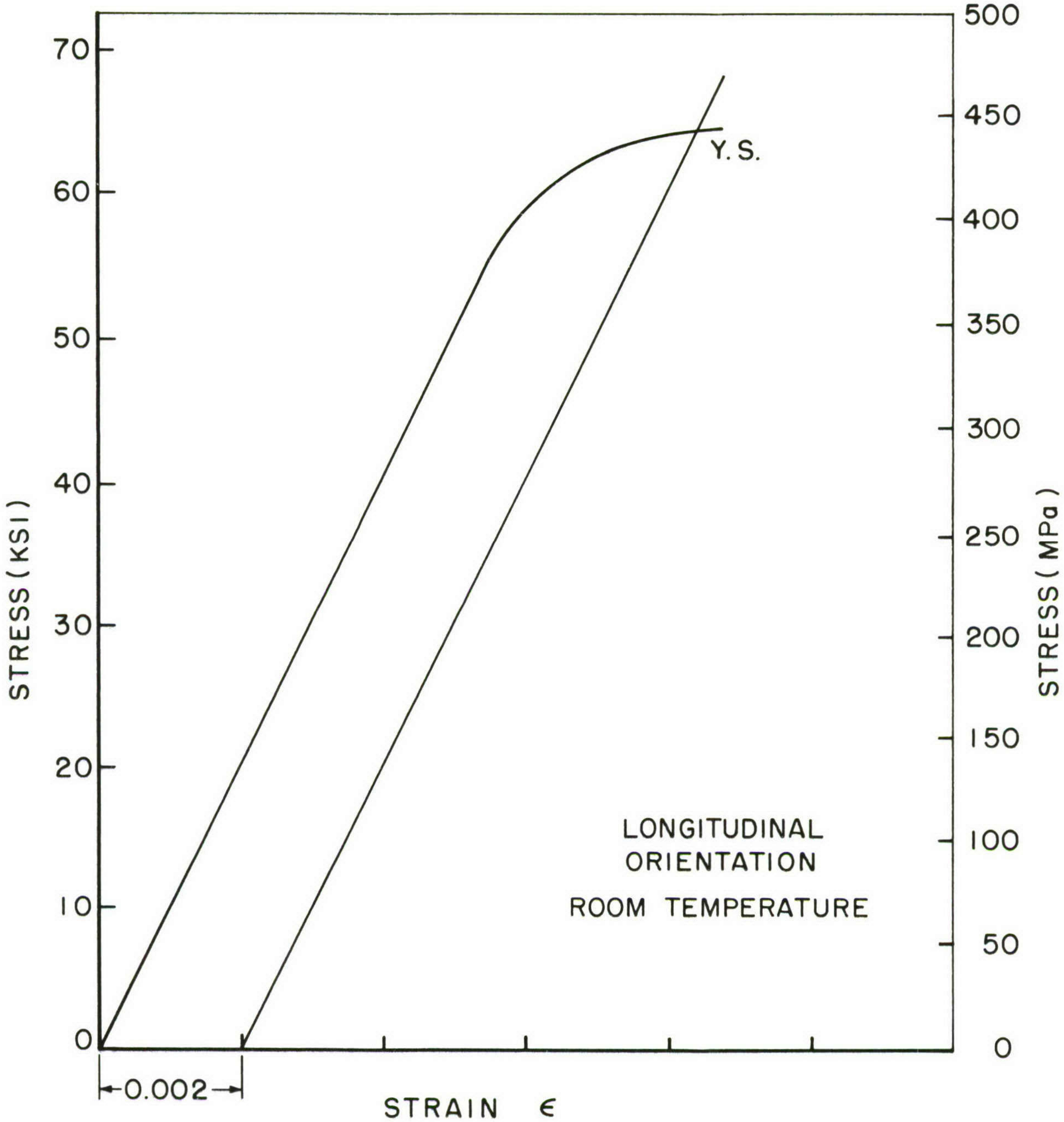



Figure 6. Typical Room Temperature Stress-Strain Curve for Aluminum 2124-T851

TABLE 4
FRACTURE TOUGHNESS PROPERTIES OF ALUMINUM 2124-T851
(THICK PLATE)

| Specimen * | Test Temp | $K_Q$ (KSI$\sqrt{IN}$) | $K_Q$ (MPa$\sqrt{m}$) | ASTM Valid? | $\frac{P_{MAX}}{P_Q}$ | Size Parameter $2.5\left(\frac{K_Q}{Y.S}\right)^2$ (inch) |
|---|---|---|---|---|---|---|
| 2LT22 | -100 °F | 31.5 | 34.6 | No | 1.066 | 0.54 |
| 2LT23 | -73 °C | 26.7 | 29.3 | Yes | 1.040 | 0.39 |
| 2LT24 | | 31.1 | 34.1 | Yes | 1.053 | 0.53 |
| | | 29.8 | 32.7 | | | |
| 2LT25 | 0 °F | 29.0 | 31.8 | Yes | 1.031 | 1.05 |
| 2LT26 | -18 °C | 30.1 | 33.0 | No | 1.051 | 1.176 |
| 2LT27 | | 28.7 | 31.5 | No | 1.147 | 1.01 |
| | | 29.3 | 32.1 | | | |
| 2LT28 | 72 °F | 29.0 | 31.8 | Yes | 1.053 | 0.50 |
| 2LT29 | 22 °C | 28.1 | 30.8 | Yes | 1.059 | 0.48 |
| 2LT30 | | 28.9 | 31.7 | Yes | 1.044 | 0.51 |
| 2LT40 | | 24.9 | 27.3 | Yes | 1.044 | 0.375 |
| 2LT41 | | 29.0 | 31.8 | Yes | 1.06 | 0.507 |
| | | 28.0 | 30.7 | | | |
| 2LT31** | 72 °F | 36.2 | 39.7 | No | 1.09 | 2.90 |
| 2LT32** | 22 °C | 35.2 | 38.6 | No | 1.08 | 2.74 |
| 2LT33** | | 29.3 | 32.1 | No | 1.31 | 1.906 |
| | | 33.9 | 37.2 | | | |
| 2LT34 | 200 °F | 28.2 | 30.7 | Yes | 1.046 | 0.54 |
| 2LT35 | 93 °C | 27.6 | 30.3 | Yes | 1.046 | 0.52 |
| 2LT36 | | 27.5 | 30.1 | Yes | 1.040 | 0.52 |
| | | 27.8 | 30.5 | | | |
| 2LT37 | 400 °F | 31.3 | 34.4 | No | 1.074 | 1.033 |
| 2LT38 | 204 °C | 32.1 | 35.2 | No | 1.089 | 1.086 |
| 2LT38 | | 32.5 | 35.7 | No | 1.134 | 1.114 |
| | | 32.0 | 35.1 | | | |

*All Fracture Toughness Tests Employed Longitudinally (L-T) Oriented Specimens.

**Specimens Were Thermally Cycled at 400 °F (204 °C) for 1000 hours Prior to Room Temperature Test.

data points for the various test temperatures employed in this program, while Figure 10 is a composite figure of lines faired through the individual data points plotted in Figures 7 through 9. For the cyclic crack growth rate tests there is no temperature effect over the temperature range of 72°F (22°C) to 200°F (93°C). The same observation was made by Hall et al., (Reference 6) over the temperature range of -65°F (-54°C) to 175°F (79°C) for two 7000-series aluminum alloys.

The specimens tested at 0°F (-18°C) and -100°F (-73°C) demonstrated improved crack growth resistance, while the 400°F (204°C) tests manifested a slight acceleration in crack growth rate when compared to the wide scatter band for the test data in the temperature range from 72°F (22°C) to 200°F (93°C).

Figure 11 is the room temperature cyclic crack growth data replotted along with the data reported in Reference 7. The room temperature constant amplitude data generated in this program and that reported in Reference 7 both have wide data scatter bands. The breadth of the data band presented in the figure has a spread in the crack growth rate for a given $\Delta K$ of a factor of 3 to 6. The crack growth data for the test material falls in the same scatter band as the referenced test data.

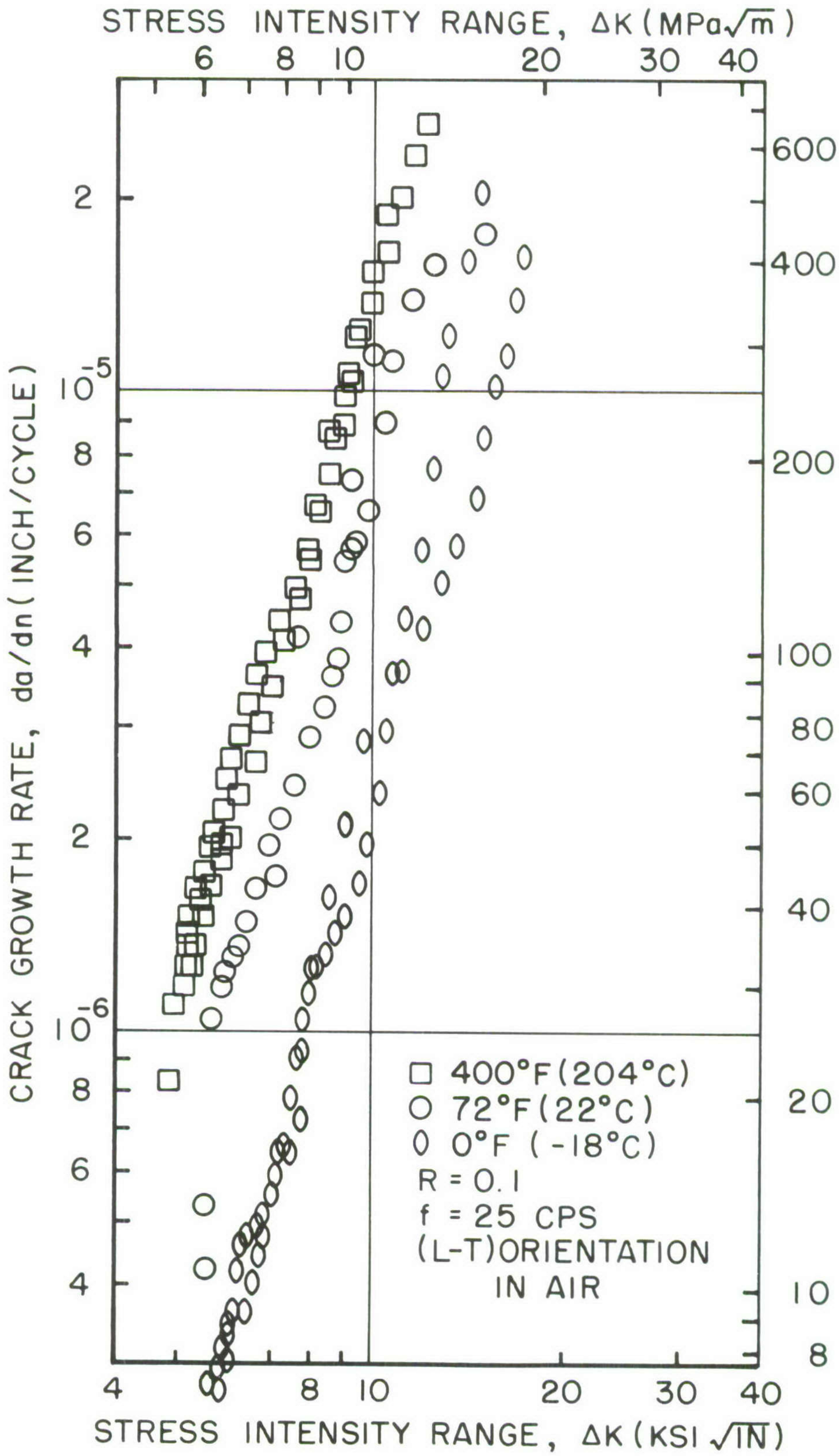



Figure 7. Al 2124-T851 (Thick Plate) Cyclic Crack Growth Rate at Test Temperatures of 0°, 72°, and 400°F

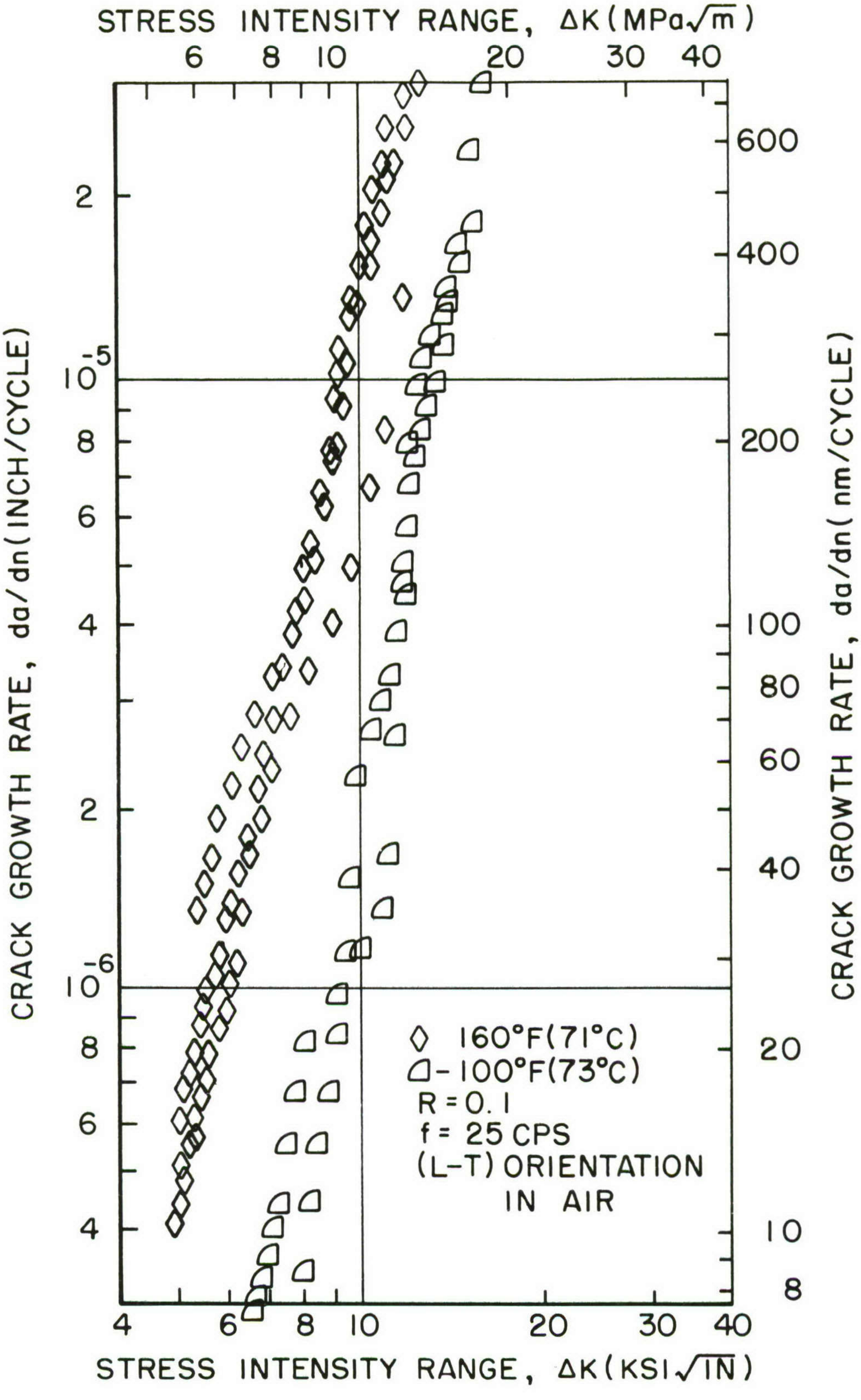



Figure 8. Al 2124-T851 (Thick Plate) Cyclic Crack Growth Rate at Test Temperatures of -100$^{O}$ and 160$^{O}$F

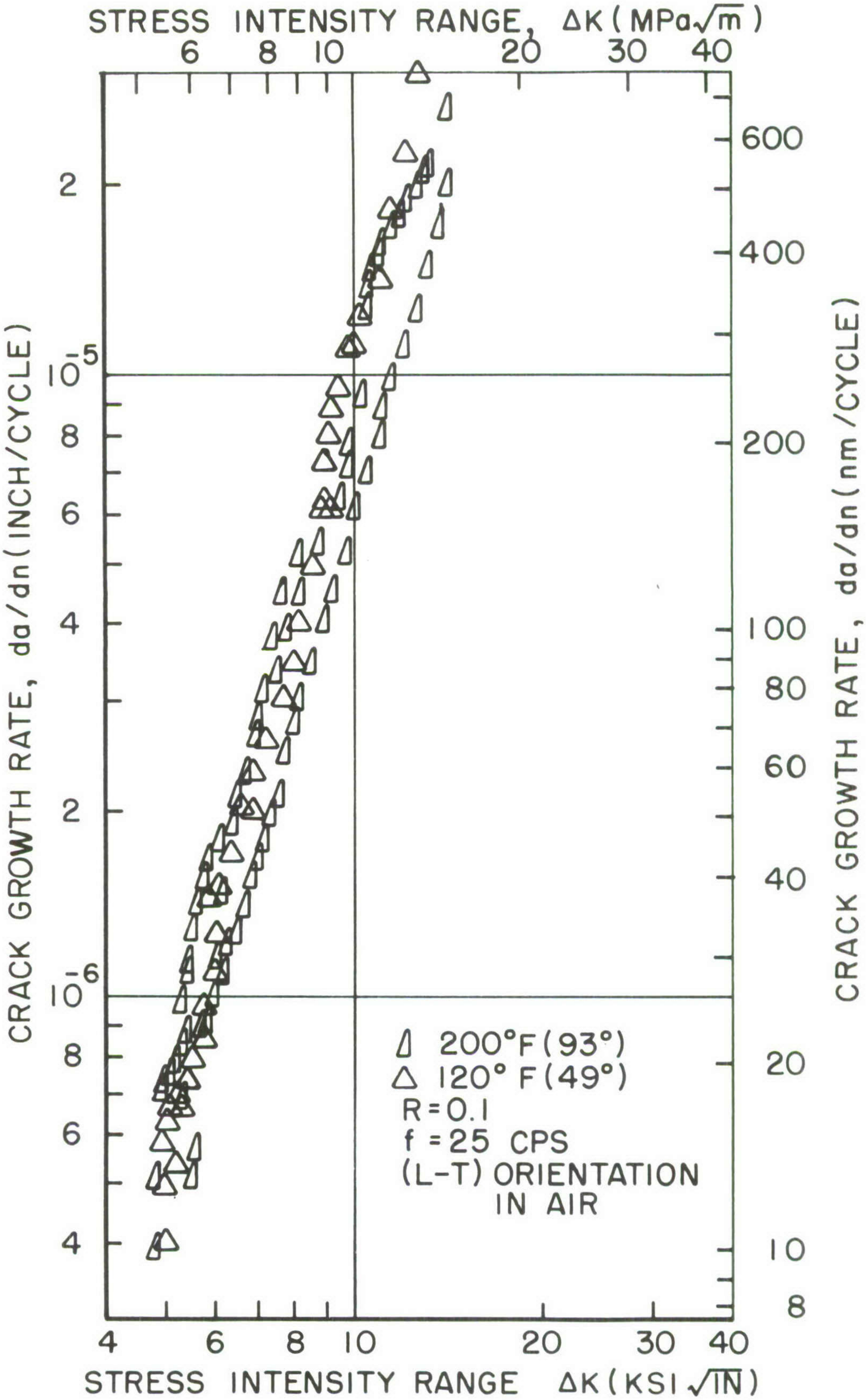



Figure 9. Al 2124-T851 (Thick Plate) Cyclic Crack Growth Rate at Test Temperatures of 200° and 120°F

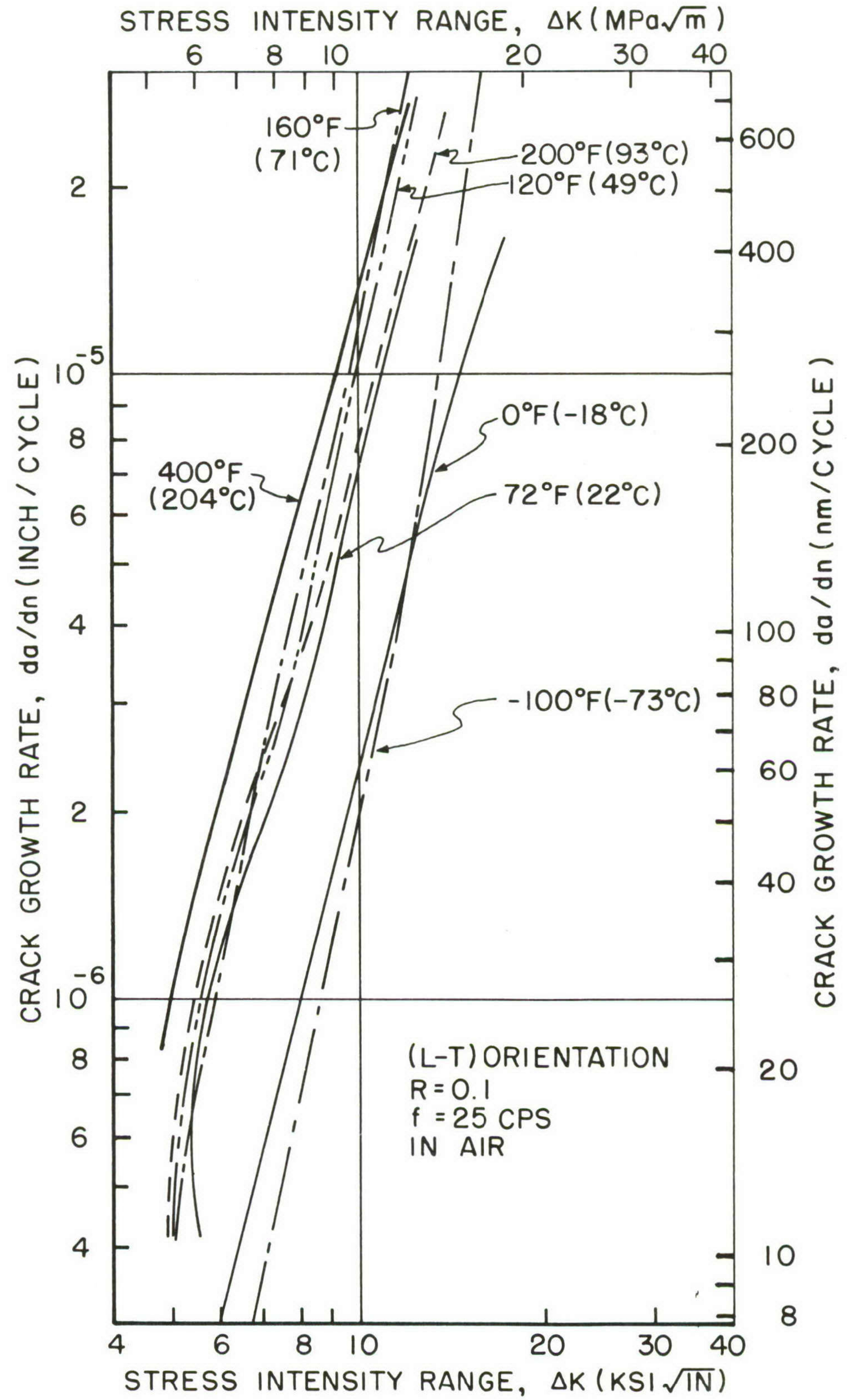



Figure 10. Al 2124-T851 (Thick Plate) Cyclic Crack Growth Rate Variation with Test Temperature

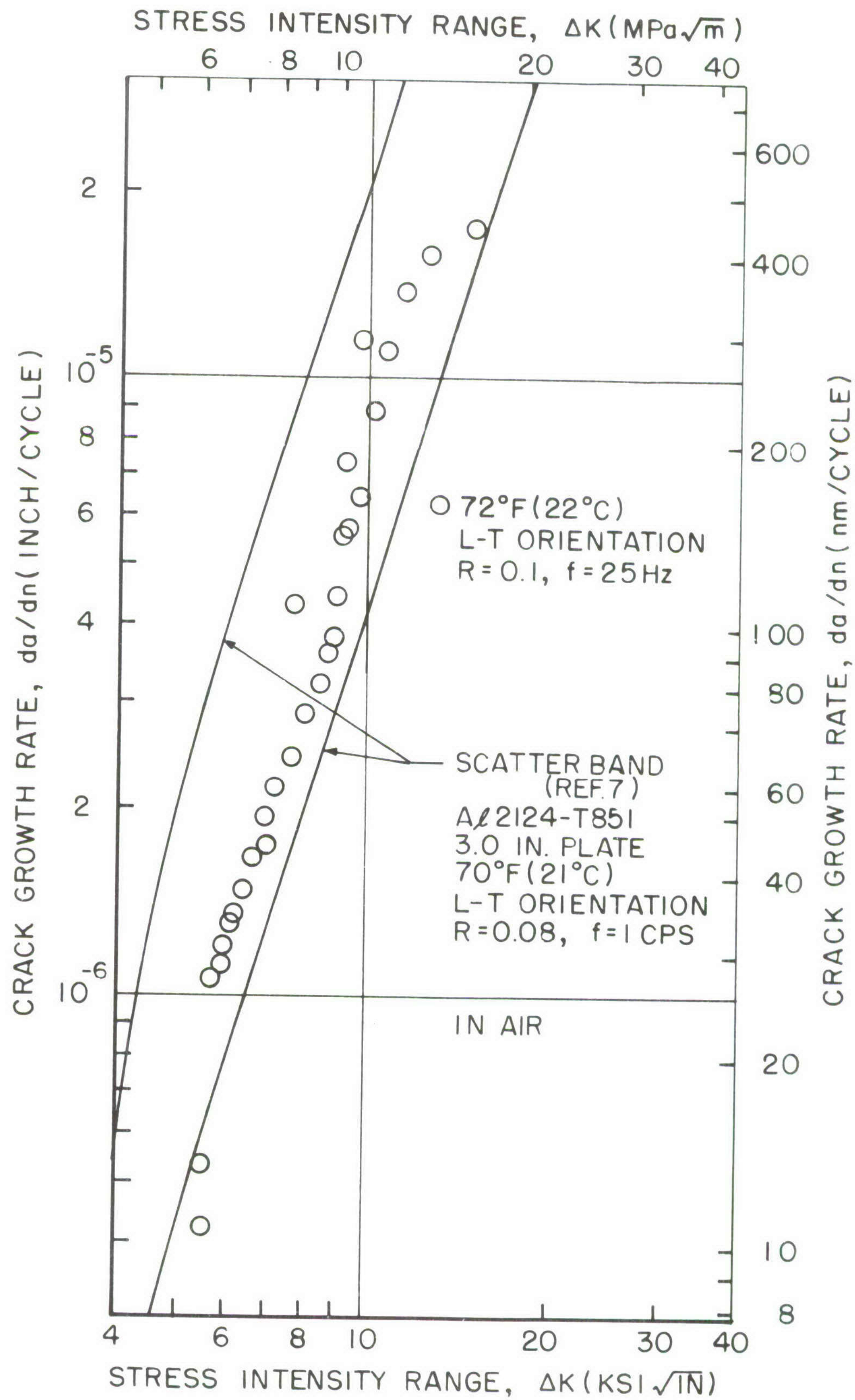



Figure 11. Al 2124-T851 (Thick Plate) Crack Growth Rate vs. Stress Intensity Range with Reference Data

## SECTION IV

## SYNOPSIS

The following conclusions are extracted from a mechanical property test program that was limited in scope and employed a single test piece of material. These findings could be altered by a more in-depth program that would include lot-to-lot variations.

1. Over the temperature rangeof -100°F (-73°C) to 200°F (93°C) there is very little variation in the material's load carrying capability.

2. A 400°F (204°C) tensile test environment produced a 26 percent loss in strength when compared with the room temperature data.

3. The 250°F (121°C) 1000-hour furnace thermal cycle prior to a room temperature test had no effect on the tensile strength.

4. The room temperature tensile strength decreased 8 percent following a 300°F (177°C), 1000 hour time-temperature exposure. The 300°F (177°C) environment approaches the maximum limit for extended service life.

5. There is no temperature effect on the cyclic crack growth rate over the temperature range of 72°F (22°C) to 200°F (93°C).

6. The 0°F (-18°C) and -100°F (-73°C) test temperature improved the cyclic crack growth resistance, while the 400°F (204°C) test temperature increased the crack propagating rate.

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